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Heli Koski, Kimmo Ollikka and Ilkka Ylhäinen

Environmental policy, green innovation and market developments

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Abstract

This report explores the implementation of various R&D subsidies and other environmental policy instruments among the OECD countries from 1990-2015 and the relations of these policies to green innovation aimed at reducing greenhouse gas emissions. Here, green innovation is measured as patented ideas of the following technology categories: i) reductions of greenhouse gas emissions related to energy generation, transmission or distribution; ii) climate change mitigation technologies related to buildings and iii) climate change mitigation technologies for the production or processing of goods.

After 2005, there was clear growth in green innovation and an expansion of markets for energy from renewable sources. The development paths of the countries differ due to the different production structures and policies adopted. Our empirical analysis suggests that the adoption of white certificate schemes promoting end-user energy savings has facilitated the generation of green innovation. The data provide further support for the positive relationship between the stringency of fossil fuel taxation and green innovation.

The literature further suggests that carbon pricing and R&D subsidies are complementary policies. R&D subsidies play a substantial role in the early stages of the transition towards clean technologies. For mature technologies, the certificate system may serve as a cost-efficient means to fulfill renewable energy obligations. Renewable energy policies also tend to be more effective in countries with liberalized energy markets. Competition and policy actions that lower entry barriers enhance green innovation.

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Tiivistelmä

Tämä raportti valottaa yritystukien ja muiden ympäristöpoliittisten ohjauskeinojen käyttöä OECD-maissa vuosina 1990-2015 sekä niiden yhteyttä vihreisiin innovaatioihin. Vihreitä innovaatioita mitataan patentoiduilla ideoilla seuraavissa teknologialuokissa: i) kasvihuonekaasupäästöjen vähentäminen liittyen energian tuotantoon, siirtoon ja jakeluun, ii) ilmastonmuutoksen hillitsemiseen tähtäävät rakennuksiin liittyvät teknologiat ja iii) ilmastonmuutoksen hillitsemiseen tähtäävät tuotantoon ja tuotteiden jalostukseen liittyvät teknologiat.

Vihreiden innovaatioiden määrä ja uusiutuvien energiamuotojen markkinat ovat kasvaneet merkittävästi vuoden 2005 jälkeen. Maiden väliset erot tuotantorakenteissa ja valituissa politiikkakeinoissa heijastuvat erilaisina kehityskulkuina. Aineistoanalyysimme viittaa siihen, että loppukäyttäjien energiasäästöihin tähtäävä nk. valkoisten sertifikaattien järjestelmä on edistänyt vihreiden innovaatioiden tuotantoa. Fossiilisten polttoaineiden verotuksen tiukkuuden ja vihreiden patentoitujen innovaatioiden määrän välinen suhde on positiivinen

Aiemmat tutkimukset osoittavat, että hiilidioksidipäästöjen hinnoittelu ja t&k-tuet ovat toisiaan täydentäviä politiikkakeinoja. T&k-tuet ovat tärkeitä ympäristöteknologioiden kehittämisen alkuvaiheessa. Kypsempien teknologioiden osalta sertifikaattijärjestelmät voivat toimia kustannustehokkaana keinona uusiutuvaan energian käyttöön liittyvien tavoitteiden saavuttamisessa. Kirjallisuus osoittaa, että uusiutuvaa energiaa koskeva politiikka on tehokkaampaa maissa, joissa energiamarkkinat on vapautettu kilpailulle. Politiikkatoimet, joilla puretaan markkinoille pääsyn esteitä edistävät vihreiden innovaatioiden tuotantoa.

Tämä julkaisu on toteutettu osana valtioneuvoston selvitys- ja tutkimussuunnitelman toimeenpanoa. (tietokayttoon.fi) Julkaisun sisällöstä vastaavat tiedon tuottajat, eikä tekstisisältö välttämättä edusta valtioneuvoston näkemystä.

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Denna rapport belyser användningen av företagsstöd och andra miljöpolitiska styrmedel i OECD-länderna under åren 1990-2015 samt deras samband med gröna innovationer. Gröna innovationer mäts med patenterade idéer i följande teknologiklasser: i) minskandet av växthusgasutsläppen som är förknippade med energiproduktionen, -överföringen och -distributionen, ii) till byggnader anknutna teknologier som strävar till att dämpa klimatförändringen och iii) till produktion och till förädling av produkter anknutna teknologier som strävar till att dämpa klimatförändringen.

Antalet gröna innovationer och marknaden för förnybara energiformer har vuxit betydligt efter år 2005. Skillnaderna i produktionsstrukturerna mellan länderna och i de valda politiska metoderna avspeglar sig som olika utvecklingsförlopp. Analysen av vårt material tyder på det att systemet med s.k. vita certifikat, som siktar på slutanvändarnas energibesparingar, har befrämjat produktionen av gröna innovationer. Den strama beskattningen av fossila bränslen har ett positivt samband med antalet gröna patenterade innovationer.

Tidigare studier ger för handen att prissättningen av koldioxidutsläpp och stöden för FoU är politiska metoder som kompletterar varandra. FoU-stöden är viktiga i begynnelseskedet av miljöteknologiernas utveckling. Då det gäller mognare teknologier kan certifikatsystemen fungera som en kostnadseffektiv metod för att uppnå de mål som är förknippade med användningen av förnybar energi. Litteraturen visar att politik som gäller förnybar energi är effektivare i länder, där energimarknaderna avreglerats och fri konkurrens råder. Politiska åtgärder med vilka man avvecklar hinder för inträde på marknaden befrämjar uppkomsten av gröna innovationer.

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Contents

1 Laajennettu tiivistelmä (Executive summary in Finnish)

Yritystukien vaikutukset innovaatioihin ja uusiutumiseen ovat olennaisia talouden pitkän aikavälin kasvun kannalta eli rakenteellisen kilpailukyvyn näkökulmasta. Pitkällä aikavälillä kansakunnat kilpailevat ennen kaikkea sillä, kuinka hyvän elintason ja hyvinvoinnin ne pystyvät kansalaisilleen tarjoamaan. Taloustieteessä innovaatiotoiminnan tukemista pidetään tärkeänä erityisesti siksi, että yksityiset markkinatoimijat eivät ota huomioon t&k-investointipäätöksiä tehdessään uusien teknologioiden tuottamiseen liittyviä ulkoisvaikutuksia eli sitä, miten tuotettu uusi tieto hyödyttää yksityistä yritystä laajemmin muita yrityksiä ja yhteiskuntaa. Tämä markkinapuute ilmenee siten, että yritykset toteuttavat vain hankkeita, joiden yksityiset odotetut tuotot ovat hankkeen kustannuksia suuremmat. Tällöin ilman julkista tukirahoitusta toteuttamatta jää joukko hankkeita, joiden yhteiskunnalliset tuotot ylittävät hankkeen kustannukset.

Ilmastonmuutoksen hillintä edellyttää laajaa energiajärjestelmien murrosta fossiilisten polttoaineiden käytöstä kohti uusiutuvia energiamuotoja. Kasvihuonekaasupäästöjen vähentäminen on ensisijainen tavoite. T&K-tuet ovat eräs ympäristöpoliittinen ohjauskeino, jonka tavoitteena on edistää kasvihuonekaasupäästöjen vähentämiseen tähtäävien teknologioiden kehittämistä (ts. vihreitä innovaatioita). Muita taloudellisia ohjauskeinoja, jotka voivat vaikuttaa vihreiden innovaatioiden kehittämiseen ja leviämiseen, ovat esimerkiksi ympäristöverot, kaupattavat päästöoikeudet sekä vihreät ja valkoiset sertifikaatit. Tuloksellinen uusiutuviin energiamuotoihin perustuvien ja kasvihuonekaasupäästöjä vähentävien teknologioiden kehittämiseen kannustava ympäristöpolitiikka edellyttää ymmärrystä siitä, miten erilaisten ohjauskeinojen käyttö vaikuttaa yritysten innovaatiotoimintaan.

Tämä raportti valottaa yritystukien ja muiden ympäristöpoliittisten ohjauskeinojen käyttöä OECD-maissa vuosina 1990-2015 sekä niiden yhteyttä vihreisiin innovaatioihin. Raportissa 1) kuvaamme tärkeimmät vihreään innovointiin potentiaalisesti vaikuttavat taloudelliset ohjauskeinot; 2) tarkastelemme Suomen ja muutamien verrokkimaiden uusiutuvan energian markkinoiden kehitystä sekä ohjauskeinovalikoimaa vihreiden innovaatioiden ja uusiutuvien energiateknologioiden edistämiseksi; 3) käymme läpi kirjallisuudessa esitettyjä tutkimustuloksia yritystukien ja ympäristöpolitiikan yhteydestä vihreään innovointiin; sekä 4) analysoimme empiirisesti ympäristöpoliittisten ohjauskeinojen ja Euroopassa ja Yhdysvalloissa patentoitujen vihreiden innovaatioiden välistä yhteyttä. Vihreitä innovaatioita mitataan patentoiduilla ideoilla seuraavissa teknologialuokissa: i) kasvihuonekaasupäästöjen vähentäminen liittyen energian tuotantoon, siirtoon ja jakeluun, ii) ilmastonmuutoksen hillitsemiseen tähtäävät rakennuksiin liittyvät teknologiat ja iii) ilmastonmuutoksen hillitsemiseen tähtäävät tuotantoon ja tuotteiden jalostukseen liittyvät teknologiat.

Uusiutuvia energiamuotoja ja niihin liittyvää t&k-toimintaa alettiin tukea öljykriisin seurauksena 1970-luvulla. Tämän jälkeen teollisuusmaissa on otettu käyttöön laajasti erilaisia uusiutuvan energian kehittämistä ja käyttöä edistäviä ohjauskeinoja kuten syöttötariffeja, uusiutuvan energian velvoitteita ja niihin liittyviä vihreiden sertifikaattien markkinoita. Viime vuosina on siirrytty aiempaa enemmän uusiutuvan energian tuotantotuen kilpailutukseen huutokaupalla. Pohjoismaat olivat ensimmäisiä maita, joissa otettiin käyttöön hiilidioksidipäästöjen verotus 1990-luvun alussa. Energiantuotannon ja energiaa paljon käyttävän teollisuuden päästöjä ohjaava Euroopan Unionin päästökauppajärjestelmä aloitti toimintansa vuonna 2005. Hiilidioksidipäästöjen hinnoittelu ei kuitenkaan ole kattavaa tai kustannustehokasta: vain 20 prosenttia globaaleista hiilidioksidipäästöistä on hinnoiteltu päästöverolla tai maksulla ja päästöistä maksettavat maksut eroavat merkittävästi eri maissa ja sektoreilla. Joissain maissa on lisäksi otettu käyttöön energiatehokkuusinvestointeihin kannustavia valkoisten sertifikaattien järjestelmiä.

Vihreiden innovaatioiden määrä ja uusiutuvien energiamuotojen markkinat ovat kasvaneet merkittävästi erityisesti 2000-luvulla. Maiden väliset erot tuotantorakenteissa ja valituissa politiikkakeinoissa heijastuvat erilaisina kehityskulkuina. Esimerkiksi Tanskassa on tuulivoimaa tuettu voimakkaasti jo 1970-luvulta lähtien, ja se onkin tuulivoiman kehittämisessä kärkimaita maailmassa. Suomessa ja Ruotsissa vesivoiman suuri osuus sähköntuotannossa on vaikuttanut muun muassa tuulivoiman alempaan hyödyntämiseen energiamarkkinoilla. Tuulivoiman osuus on kuitenkin noussut voimakkaasti viime vuosina Suomen ja Ruotsin lisäksi myös Britanniassa ja Saksassa. Saksassa myös aurinkovoiman kasvu on ollut vahvaa korkeiden syöttötariffimaksujen myötä.

Aineistoanalyysimme tarjoaa uutta tietoa ympäristöpoliittisten ohjauskeinojen ja vihreiden innovaatioiden välisestä riippuvuussuhteesta. Estimointituloksemme viittaavat siihen, että energiatehokkuuteen ja loppukäyttäjien energiasäästöihin tähtäävä valkoisten sertifikaattien järjestelmä on edistänyt vihreiden innovaatioiden tuotantoa. Valkoisten sertifikaattien järjestelmä oli otettu käyttöön aineiston kattamina vuosina vain neljässä EU-maassa (ts. Iso-Britanniassa, Italiassa, Ranskassa ja Hollannissa). Kokemukset järjestelmän avulla saavutetuista energiasäästöistä ovat olleet kannustavia. Tutkimustulostemme sekä aiempien energiasäästötavoitteiden saavuttamiseen liittyvien havaintojen valossa voisi olla hyödyllistä tutkia tarkemmin valkoisten sertifikaattien järjestelmän kustannustehokkuutta ja vaikuttavuutta Suomen oloissa.

Aineistoanalyysimme tulokset osoittavat, että fossiilisten polttoaineiden verotuksen tiukkuuden ja vihreiden patentoitujen innovaatioiden määrän välinen riippuvuussuhde on positiivinen. Tämä tulos on samansuuntainen aiempien tutkimusten kanssa, joiden mukaan ympäristöverot suuntaavat teknologista kehitystä kohti puhtaampia innovaatioita. Tutkimuslöydösten perusteella vaikuttaa uskottavalta, että yritysten tiedossa olevat energiaveronpalautukset saattavat pienentää niiden kannustimia investoida kasvihuonekaasupäästöjen vähentämiseen tähtäävien teknologioiden tutkimukseen ja kehitykseen. Täten energiaveronpalautuksilla voi olla vihreitä innovaatioita vähentävä vaikutus.

Aineistomme osoittaa, että enemmän julkisia T&K-investointeja uusiutuviin energialähteisiin ja energiatehokkuuteen tekevissä maissa syntyy enemmän patentoitavia innovaatioita, jotka koskevat kasvihuonekaasupäästöjen vähentämistä liittyen energian tuotantoon, siirtoon ja jakeluun. Emme pysty tekemään vahvoja johtopäätöksiä T&K-tukien ja vihreiden innovaatioiden välisestä suhteesta, koska käyttämämme OECD:n tietokanta on puutteellinen ympäristötukien osalta. Aiempien tutkimusten perusteella voidaan kuitenkin päätellä, että T&K-tuet edistävät innovaatiotoimintaa. Kirjallisuus osoittaa lisäksi, että hiilidioksidipäästöjen hinnoittelu ja t&k-tuet ovat toisiaan täydentäviä politiikkakeinoja. T&k-tuet ovat tärkeitä ympäristöteknologioiden kehittämisen alkuvaiheessa. Kypsempien teknologioiden osalta sertifikaattijärjestelmät voivat toimia kustannustehokkaana keinona uusiutuvaan energian käyttöön liittyvien tavoitteiden saavuttamisessa.

Vaikka kirjallisuus viittaa siihen, että T&K-tuet voivat tehokkaasti täydentää muita politiikkainstrumentteja, näyttää siltä, että vaikuttavimpia työkaluja vihreiden innovaatioiden tukemiseen ovat verot tai veron kaltaiset ympäristöpoliittiset instrumentit. Keppi voi toimia parempana kannustimena kuin porkkana (esim. tiukempi fossiilisten polttoaineiden verotus) kasvihuonekaasupäästöjen vähentämiseen tähtäävien innovaatioiden kehittämiselle. Kirjallisuus osoittaa, että uusiutuvaa energiaa koskeva politiikka on tehokkaampaa maissa, joissa energiamarkkinat on vapautettu kilpailulle. Politiikkatoimet, joilla puretaan markkinoille pääsyn esteitä edistävät vihreiden innovaatioiden tuotantoa.

2 Introduction

Innovation and economic renewal are essential to long-term economic growth. In the long run, nations ultimately compete to provide maximum welfare for their citizens. Support for innovation is considered well justified, as private decision-makers do not take into account the positive externalities of their actions in their research and development (R&D) decisions; the new knowledge generated may benefit not only a firm itself but also other companies and society more broadly. Consequently, without public support, many R&D projects whose private expected returns do not exceed costs – while their social returns do exceed costs – do not materialize.

Innovation further drives the creation and development of (new) markets. Currently, the market for forms of renewable energy is one of the markets whose evolution will fundamentally affect not only short-term social welfare but also the welfare of future generations. A major target of environmental policy is to reduce negative externalities related to energy production that, by and large, arise from greenhouse gas emissions. The speed at which new technologies that reduce greenhouse emissions and mitigate detrimental effects of climate change are developed, adopted and implemented is strongly affected by the appropriateness of selected environmental policy instruments and regulations.

This report aims to explore R&D subsidies and the implementation of various other forms of environmental policy instruments (such as feed-in tariffs, green and white certificates and taxes on pollution) among the OECD countries and the relations of these policies to green innovation aimed at reducing greenhouse gas emissions. Here, green innovation is defined as patented ideas of the following technology categories: i) the reduction of greenhouse gas emissions related to energy generation, transmission or distribution; ii) climate change mitigation technologies related to buildings and iii) climate change mitigation technologies for the production or processing of goods. We use both descriptive measures and an empirical analysis to explore the compiled data from 1990-2015, thus covering the patenting activities and various environmental policy measures of OECD countries.

The rest of the report is organized as follows. Section 3.1 introduces the key environmental policy instruments used by OECD countries. Section 3.2 describes the development of markets for green energy in Europe (as OECD-wide data were not available). Section 4 discusses the findings of previous studies concerning the relationship between the use of different environmental policy instruments and green innovation. Section 5.1 introduces the data used for the empirical estimations. Section 5.2 sheds light on developments in environment-related patent applications filed with the European Patent Office (EPO) and the United States Patent and Trademark Office (USPTO) over time. Furthermore, this section compares the OECD countries' positions as patentees in the selected technology categories. Section5.3 describes the adoption of various environmental policy instruments among the OECD countries. Section 6 presents the estimation results. Section 7 concludes.

3 Environmental policy instruments and markets for green energy

Environmental policies, technological innovations and investments in new energy technologies go hand in hand (e.g., Johnstone et al. 2010, Popp et al. 2011). This section first provides insights on the key environmental policy instruments adopted by the OECD countries that affect both green innovation and the development of markets for green energy (Section 3.1). It then provides a background information on how the markets for green energy have developed in Finland and in some reference countries. We further give a brief overview of the environmental policy instruments that have influenced the development of clean energy technologies in these countries.

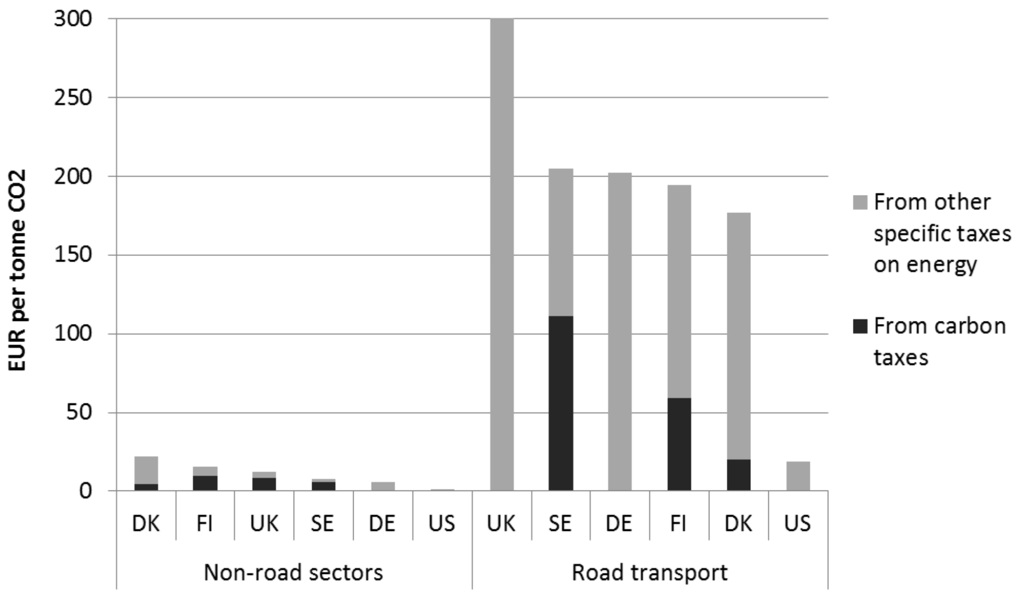
3.1 Environmental policy instruments

This section primarily discusses economic or market-based environmental policy instruments, such as tradable permits, subsidies and taxes on pollution, used to facilitate the transition towards clean technology. Finland, Sweden, Norway and Denmark were the first countries to implement carbon taxes, and thus carbon pricing, in the beginning of the 1990s. The European Union Emissions Trading System (EU ETS) started its operations in 2005 and has been the largest carbon pricing initiative thus far. Approximately 50 different carbon pricing policies have been implemented or are scheduled to be implemented globally. Half of the carbon pricing initiatives are emissions trading systems (national or subnational) and another half are national carbon taxes. However, these initiatives cover only approximately 20 percent of global greenhouse gases (World Bank and Ecofys 2018.) In addition, there is broad variation in prices between the different initiatives, and prices are generally far from the level required to meet, for instance, the objectives of the Paris Agreement.

Figure 1 presents the OECD's estimates of the average effective tax rates on carbon emissions generated from energy use in non-road sectors and through road transport in some selected countries. These figures do not include EU ETS prices or all energy tax exemptions or refunds to which, for instance, energy intensive industries are entitled. Generally, effective carbon prices are much higher in the road transport sector than in other sectors. One must also bear in mind that carbon pricing is not the only objective of energy taxation. Cost-effective emission abatement requires, however, that the price placed on CO2 emissions should be the same irrespective of its source.

Carbon pricing, whether implemented through taxes or an ETS, provides incentives for emitters to reduce their emissions cost efficiently and to further innovate new and less carbon-intensive technologies. Currently, these objectives are not fully met, as prices are generally at excessively low levels, prices differ between sectors and geographic areas, and global coverage is not sufficient.

Figure 1. Average effective tax rates on carbon emissions from energy use in non-road and road transport sectors.



Source: OECD.

Though carbon pricing is regarded as the most important climate policy instrument, an optimal policy portfolio requires the use of additional instruments. The reason for this requirement is that pollution is not the only externality related to climate change. Knowledge accumulated through research and development (R&D) or learning by doing are rationales for subsidizing R&D or the deployment of renewable technologies. In addition, imperfections in the market demand for energy efficiency may call for policy instruments to support investments in energy efficiency. These imperfections may arise from a lack of credible information, landlord-tenant arrangements, myopic behavior, or an undervaluation of energy efficiency in the purchase of energy-using appliances or homes (see, e.g., Fischer et al. 2017 and references therein).

Fischer et al. (2017) argue, based on their simulation study of the US electricity sector, that emissions pricing is the most cost-effective means of reducing emissions. However, with multiple market failures, emissions pricing is not fully efficient on its own. Subsidies correcting R&D market failures are important as well, and they are more important than correcting learning-by-doing spillovers of a similar scale. Fischer et al. (2017) show that optimal learning-by-doing subsidies for renewable technologies are relatively low. Moreover, instruments correcting the undervaluation of energy efficiency may have a considerable effect on emission reduction costs because a demand-side market failure affects the entire electricity market in contrast to renewable energy generation, which currently represents only a small share of total energy supply. Acemoglu et al. (2016) make a similar argument. Carbon pricing and R&D subsidies are complementary policies, and R&D subsidies play a big role in the beginning of the transition to clean technologies.

Renewable energy policies can be classified as either demand-pull (e.g., feed-in tariffs or green certificates) or technology-push (e.g., R&D subsidies). European and other countries have implemented a wide range of different types of renewable energy support schemes (Kitzing et al. 2012). Support for renewable energies started in the early 1970s as a result of the oil crisis, when renewable energy R&D programs were introduced in many OECD countries. Subsequently, investment and tax subsidies, as well as feed-in tariffs, were mainly used in the 1980s and 1990s. Since 2000, renewable energy obligations and tradable green certificate systems have been implemented in various countries. Recently, many countries have moved to tender mechanisms in particular because tariff systems have proven to be a relatively expensive means to support renewable energy. In Europe, the European Commission has directed this change, e.g., through its Guidelines on State Aid for Environmental Protection and Energy.

In the feed-in tariff system, the electricity producer receives a higher price for the electricity it produces than the market price. The two most widely used tariff formats are a guaranteed price tariff and a premium tariff. In the guaranteed price system, the electricity producer is guaranteed a minimum price for electricity. The feed-in tariff is the difference between the guaranteed price and the price of electricity when the market price of electricity falls below the guaranteed price. When the price of electricity is higher than the guaranteed price, the feed-in tariff is not paid. In the price premium, the feed-in tariff consists of the premium paid on top of the normal market price of electricity. The price received by the producer varies with the price of electricity. From the producer's perspective, the difference between these two formats is the risk of revenue: a guaranteed price provides the producer a secure return and reduces investment risk.

In addition to differences in tariff formats, tariff systems vary in many respects (e.g., tariff levels and duration) across countries. The granting of a tariff may also be subject to a specific cumulative capacity limit beyond which the feed-in tariff is not paid for new projects. The return on investment is different for mature and relatively cost-efficient technologies compared to some new technologies still in the pilot phase and far from market entry. This difference is also reflected in tariffs paid to different technologies. As a general trend (at least in Europe), the feed-in tariffs paid to solar power have been higher than the subsidies for other technologies (Jenner 2012).

Green certificate systems are based on renewable energy obligations. Under a renewable energy obligation system, a producer, reseller or consumer is obliged to produce, transmit or consume a certain amount of its electricity through electricity produced from renewable resources. In the renewable energy certificate system (or in green certificate system), renewable electricity is certified. The entity with the renewable energy obligation must hold a certain number of certificates in accordance with the obligation over a certain time period. Certificates can be traded in the same way as other conventional commodities. The price of a certificate will increase when the obligations of renewable energy are not met. Increased prices incentivize producers to produce more renewable energy and thus more certificates for the market. The green certificate system serves as a cost-efficient way to fulfill renewable energy obligations, but it favors mature technologies.

The tariff system may be supplemented with a tendering procedure. For instance, the authority provides support for a certain level of renewable energy production at auction. The producers participate in the auction, where they bid for the level of support they desire for their projects or for the electricity they produce. The authority will grant support from the lowest bid until the targeted amount of renewable energy projects or capacity is met. The tariff level of the winning projects will be determined by the last approved bid or by any other auction design rule. Currently, 18 countries have implemented or are planning to implement tendering procedures for one or more form of renewable energy technology in the EU. While most tenders are technology-specific, technology-neutral tenders are being conducted where more than one technology competes in the same tender. For instance, Finland conducted a technology-neutral tender at the end of 2018.

White certificate scheme sets obligations and targets to energy savings

White certificate scheme is a type of energy efficiency obligation scheme. The white certificate system relies on market-based mechanisms. An independent certifying body obligates energy suppliers and/or distributors to fulfil annually set energy saving targets and issues white certificates that compensate materialized energy savings of the obligated parties. Each certificate provides evidence that a certain amount of energy saving has been reached and secures a property right over this additional saving. The obligated parties may achieve energy savings by selecting technology and end-user sectors through which they invest in energy efficient projects (within limits of national scheme implementation) and/or buy white certificates from other parties.

The nature of this policy instrument is tax-like in a sense that the energy supplier or distributor needs to invest its own resources to achieve the set energy saving goal. When the energy saving actions of the obligated supplier/distributor are not sufficient, it may purchase white certificates from end users from which energy saving projects obtained the certificates. Furthermore, white certificate scheme resembles emissions trading system in a sense that both emissions allowances and white certificates may be sold in secondary markets. These secondary markets differ, however, in their geographical coverage. Emissions allowances can be bought and sold throughout the EU-wide market, while the secondary markets for white certificates are country-specific.

Only a small number of countries have implemented a white certificate scheme by setting energy saving obligations for energy suppliers and/or distributors. In the four European countries (i.e., the UK, Italy, France and Denmark) that have adopted the white certificate scheme, the sectoral coverage of eligible projects varies (as well as other characteristics of the instruments; see., e.g., Togeby et al., 2007; Rezessy and Bertoldi, 2010). In the UK, white certificates can be obtained only from energy savings related to the projects that concern residential consumers. In contrast, in Italy, all sectors are covered. In France, the building sector (including residential, commercial and public buildings) was chosen as the major target while the energy saving projects of other sectors are also eligible. In Denmark, the white certificate scheme design made eligible energy saving projects of all other sectors except those of the transport sector.

Our empirical analysis further considers other environmental taxes. For example, some countries, such as Sweden, have imposed taxes on SO_2 and NO_x in addition to the CO_2 tax. On the other hand, Finland, for instance, does not have a separate SO_2 or NOx tax, as these emissions are controlled by separate emission limit values. We also control for the ratification of the Kyoto Protocol, as various prior studies suggest that signing or ratifying the Kyoto Protocol has a positive impact on green innovation. International environmental agreements may have substantial impacts on innovation, as they contribute to the international market outlook on clean technologies. The Kyoto Protocol was signed in 1997, and it came into force in 2005. The Protocol set specific emissions reduction targets for industrialized countries for the two commitment periods, i.e., 2005-2012 and 2013-2020. However, developing countries, including China, did not have any reduction targets. In addition, the US did not ratify the Protocol, Canada announced its withdrawal from the Kyoto Protocol in 2011, and Japan and Russia did not adopt any reduction targets for the second commitment period. Hence, The Kyoto Protocol failed to reduce global emissions.

The design of an environmental policy instrument and, particularly, whether an implemented renewable energy policy is *technology-neutral* or *technology-specific* may affect innovation and the development of energy markets more broadly. Technology-specific policy focuses on promoting development in certain technology fields or sectors, such as R&D subsidies targeted to a specified renewable energy form or feed-in tariff schemes for solar and wind energy. Prior research suggests that such policy instruments may increase the risk of lock-in to the technology that appear to be the most cost-efficient at the time of policy decision-making but which may become inefficient over a longer term comparison (Schmidt et al., 2016). Instead, generic subsidies for R&D and the schemes that set prices to environmental externalities (e.g., emission taxes and emissions trading schemes) are technology neutral and allow markets determine the direction and speed of technology deployment. In other words, green and white certificate schemes promote competition between new technologies, while feed-in tariffs subsidize specific forms of green innovation over competing alternatives.

Table 1. Market-based policy instruments promoting renewable energy forms

Instrument type	Technology neutral	Technology specific
Subsidy	Generic R&D subsidies	Specified R&D subsidies Feed-in tariffs

"Reverse subsidy" or tax-like instrument	Green & white certificates Carbon pricing Environmental taxes	

Table 1 summarizes how different market-based policy instruments promoting renewable energy forms are divided into subsidies and "reverse subsidies" or tax-like instruments and into technology-neutral and technology-specific renewable policy tools.

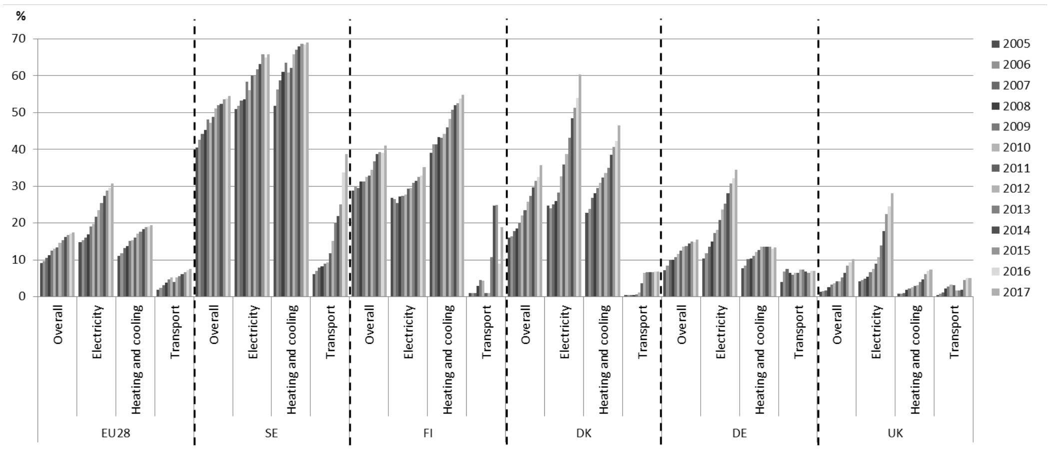
3.2 Development of markets for green energy

The share of energy generated from renewables increased moderately in EU28-countries (and in Finland) between 1990 and 2005. Sharper increases have occurred since 2005. However, the development paths of the countries differ. These paths are influenced by the different energy production structures in place in the countries and by the policies adopted. Figure 2 presents shares of energy generated from renewable sources in the EU and in some selected countries, and Figure 3 illustrates the development of electricity generation from renewable sources.

In Sweden and Finland, shares of renewables from total energy consumption were already fairly high in the beginning of 2000. In Sweden, this phenomenon was due to the high share of hydropower, and in Finland, this was due to high shares of hydro power and biofuels used for electricity and heat production. In Denmark and especially in Germany and the UK, renewable shares have been much lower. However, shares have increased rapidly over the last fifteen years, mainly due to an increased use of wind power for electricity generation. In Germany, in addition to wind power, electricity generation from solar power has increased significantly.

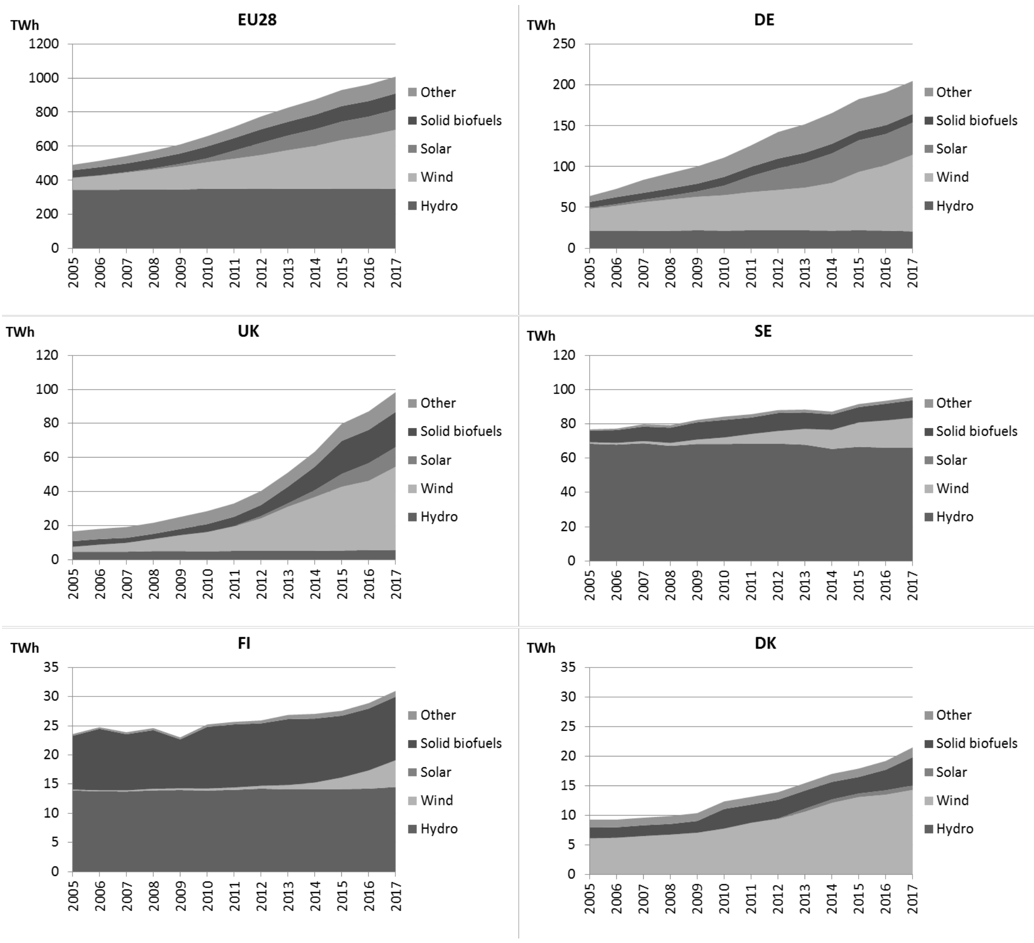
Next, we briefly discuss the development of renewable energy in the electricity market in the selected countries and the main policy instruments supporting renewable energy in these countries.

Figure 2. Share of energy generated from renewable sources in EU: overall, for the electricity generation sector, for the heating and cooling sector and for the transport sector.



Source: Eurostat.

Figure 3. Electricity generation from renewable sources.



Source: Eurostat.

Germany

Goals to achieve nuclear phase-out by 2022 and a 80 percent target for the share of renewable energy of total electricity consumption by 2050 have been the main drivers of German energy policy in recent years. Feed-in tariffs for renewable energy were already introduced in the early 1990s, and these tariffs obliged electricity network operators to accept green electricity in their grids and to pay 90 percent of the electricity resale price to electricity producers. The tariff system was reformed in the beginning of the 2000s, and after the reform renewable energy producers were paid fixed feed-in tariffs. Tariff levels have been relatively generous, especially for solar power. The production of wind and solar power has increased rapidly over the last fifteen years. While wind and solar power production levels in 2005 reached 27 TWh and 0.6 TWh, respectively, in 2017, these levels reached 94 TWh and 39 TWh, respectively. The share of wind and solar has rapidly increased the share of renewables of total electricity production. However, the growth of solar power has stabilized in recent years. The feed-in tariff system has been very expensive. Total payments for renewable energy subsidies in 2000 amounted to approximately 1 billion euros and have increased to over 20 billion euros in recent years. On average, the feed-in tariff for solar power in 2016 was 32.3 ct/kWh and that for onshore wind was valued at 10.5 ct/kWh.[1] The expenses are being collected from electricity customers, and this has increased the electricity prices paid by them. The average household paid over 29 ct/kWh for electricity consumption in 2017 on average, and renewable energy surcharge (EEG Umlage) was valued at 6.9 ct/KWh. Energy intensive industries are mostly exempted from the EEG surcharge. Since 2015, Germany has used tenders to allocate renewable energy subsidies. Several auctions for different technologies are organized annually. Average funding awarded for ground-mounted PV installations amounted to 9.17 ct/KWh in the first pilot auction held in April 2015. However, auction clearing prices have come down. In October 2018, average funding for ground-mounted PV installations was valued at 4.69 ct/KWh. In the same auction, average funding for onshore wind was valued at 6.26 ct/kWh, but in February 2018, it was valued at 4.73 ct/kWh.

UK

[1] https://www.bdew.de/media/documents/20170710_Foliensatz-Erneuerbare-Energien-EEG_2017.pdf

The UK has developed experience from the implementation of various kinds of renewable energy subsidy programs. The UK used auctions in as early as the 1990s, but the program (the Non Fossil Fuel Obligation, NFFO) failed in terms of project implementation. Only a few of the projects were realized (Mitchell and Connor 2004). The UK was also the forerunner in the adoption of white certificate scheme: it implemented the scheme already in 2002. From 2002-2017, the main support mechanism was the Renewables Obligation (RO) program, which was a green certificate system. Under the RO system, wind power capacity and production and power production from solid biofuels rapidly improved. In 2005, wind mills produced 2.8 TWh of all electricity in the UK, but in 2017, wind power production was already valued at 48.8 TWh. The corresponding figures for solid biofuels are 3.4 TWh for 2005 and 20.8 TWh for 2017. Over the last five years solar power production has improved; in 2010, there was almost no production by solar power in the UK, but in 2017, production had already reached 11.5 TWh. The RO system was closed in 2017 and was replaced with the Contracts for Difference (CfD) program. The Contracts for Difference program is a tariff system based on the difference between the market price and an agreed upon “strike price”, which serves as a guaranteed payment the producer receives for its electricity production. There have been two CfD allocation rounds thus far (in 2015 and 2017), and the next allocation round will occur in the spring of 2019. For instance, the clearing price in the first allocation round (2015) was valued at 114.39 £/MWh (133.1 €/MWh)[2] for offshore wind and at 82.5 £/MWh (96 €/MWh) for onshore wind for delivery year 2018/19. Solar PV clearing prices for the delivery year 2016/17 were valued at 79.23 £/MWh (92.19 €/MWh), but the allocated capacity for solar power was much lower than that for wind power.[3]

Sweden

Sweden boasts some of the highest shares of renewable energy in Europe due to its high share of hydro power resources. Over 40 percent of all Swedish electricity production is produced through hydro power. Sweden implemented a green certificate system in 2003 that has been a success at least in terms of sending more renewable

[2] Based on the exchange rate on April 5, 2019: 1€ = 0,8594£.
[3] See: https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference. The second CfD auction was for ‘less established’ technologies. The clearing price in the second allocation round in 2017 was, for example, valued at 74.75 £/MWh (86.92 €/MWh) for offshore wind, biomass CHP and advanced conversion technologies for the delivery year 2020/21.

energy to power markets. The certificate system has mostly boosted mature technologies, such as CHP plants using biofuels and wind power in particular (Fridolfsson and Tangerås 2013). Wind power production levels increased from 0.9 TWh in 2005 to 17.2 TWh in 2017. The certificate price has average at 15 – 20 euros/MWh. The highest prices were seen in the summer of 2008, when the monthly average price exceeded 30 euros/MWh. The average price in 2018 was valued at 14.1 euros/MWh.[4]

[4] https://cesar.energimyndigheten.se/

Denmark

Denmark is a leading country in wind power, and it is producing the most energy from wind turbines per capita of all OECD countries. Denmark started to promote wind energy in as early as the mid-1970s, first through an R&D support program for all energy areas including wind energy (1976) and later through investment subsidies for the installation of wind turbines (1979-1989). From the mid-1980s, private wind turbine owners received a partial refund for energy and environmental taxes. A feed-in tariff for wind energy was introduced in 1993. Utilities companies were obligated to purchase electricity from wind producers at 85 percent of consumer prices. Feed-in tariffs were modified in 2001 towards the development of a premium-based system under which a premium is paid on top of the electricity market price. In 2006, Denmark adopted the white certificate scheme being one of the first countries to implement the scheme. In 2017, Denmark produced 40 percent of its electricity from wind power. Total wind production was valued at 14.3 TWh in 2017. Denmark is also turning to the use of auctions to promote renewable energy. In 2018, Denmark held a technology neutral tender for onshore wind turbines and solar PV installations. The weighted average price premium of the winning bids was valued at 0.31 ct/kWh.[5]

Finland

Finland has used two main renewable sources for electricity production: biofuels and hydro. In 2005, these sources accounted for 59 and 39 percent of all renewable energy production, respectively. Finland implemented the feed-in tariff system in 2011. Producers of electricity generated from wind, biogas and biomass were eligible for a feed-in tariff. The target price for wind power was significantly high (83.5 euros/MWh), which attracted several new projects. However, the capacity limit of the tariff system for wind energy (2500 MVA) was quickly met. In 2010, the production of wind power was valued at 0.3 TWh whereas in 2017 total wind power production was already valued at 4.5 TWh. In 2017, the share of wind power production was 15 percent of all renewable electricity production and 5 percent of total electricity production. In 2018, Finland adopted a tender-based premium scheme for new producers of electricity from wind, solar, biogas, biomass wood fuel and wave power. Support for 1.4 TWh of annual production was auctioned. All winning bids were based in wind energy with the average premium price set to 2.52€/MWh, and the highest accepted bid was 3.97 €/MWh.

[5] https://ens.dk/en/our-services/current-tenders/tender-scheme-wind-and-solar-pv-2018-2019

4 What can we learn from the literature?

Country-level studies

There have been a growing number of cross-country studies on the effectiveness of policy instruments in fostering renewable energy innovation. Johnstone et al. (2010) found, in analyzing the patents of 25 OECD countries in 1978-2003, that public R&D expenditures facilitate the patenting of renewable technologies. Moreover, obligations and quantity-based instruments enhance the patenting activity of more mature and low-cost technologies, such as wind power. More targeted price schemes, such as feed-in tariffs and investment incentives, on the other hand, have had a positive effect on the patenting of those technologies still in early phases of development or that are more costly, such as solar power.

The patenting of energy technologies closely relates to energy market conditions and energy prices. Popp (2002) used US patent data from 1970 to 1994 to study the impact of energy prices on the patenting of energy-saving technologies. Energy prices had a positive impact on new innovations. The quality of the stock of knowledge available to the inventor was also an important factor in inducing new energy innovations. Nesta et al. (2014) showed that competition in electricity markets may also play a role in fostering green innovation; renewable energy policies are more effective in countries with liberalized energy markets. These authors also found that renewable energy policies are important for the innovation actions of high-quality patents (i.e., triadic patents filed in all three major patent offices: American, European and Japanese patent offices) whereas for low-quality patents it is electricity market competition that encourages patenting. Furthermore, Nicolli and Vona (2016) found that increasing competition in electricity markets by lowering entry barriers has a positive effect on the innovation of renewable technologies used especially by small and independent power producers (wind and solar power).

All of the above studies on effects of the signing or ratification of the Kyoto Protocol show that the protocol has had a significantly positive effect on the innovation of renewable energy technologies. Progress in international climate negotiations affords companies and countries a signal of the good future market prospects of new energy technologies.

Moreover, both domestic and foreign policies, and thus policy spillovers between countries, are important. Dechezleprêtre and Glachant (2014) showed, in studying wind energy patents, that the marginal effect of domestic demand-pull policies on the rate of innovation is much greater than the marginal effect of foreign demand. However, the aggregate effect of foreign demand on innovation is stronger overall. However, barriers to trade, lax IP rights and strong controls over capital markets weaken the positive influence of foreign demand and on the transfer of patented inventions. Peters et al. (2012) presented similar results for solar photovoltaic technologies. In addition, Constantini et al. (2017) showed that 1) the balanced use of demand-pull and technology-push policy instruments in one country and 2) cross-country similarities in policy instruments between countries engaged in bilateral trade positively influence innovation performance in energy-efficiency technologies in the building sector.

Böhringer et al. (2017) analyzed renewable energy policies adopted in Germany. Focusing on one country enables one to model policies more accurately. The implementation of policy instruments varies across countries and technologies, and many aspects of policies are difficult to measure and compare across different countries. Böhringer et al. (2017) found that the German feed-in tariff scheme has encouraged patenting in renewable energy technologies.

However, Böhringer et al. (2017) found that the effect of public R&D funding on patent applications is statistically insignificant. This result stands in contrast to those of some other studies (e.g., Johnstone et al. 2010; Nicolli and Vona 2016) but is consistent with the results of Nesta et al. (2014).

Generally, according to a literature review by Becker (2015), R&D subsidies, taking the form of tax credits and direct subsidies to firms, have a positive impact on innovation. First, the most recent literature shows that R&D tax credits have a positive effect on firms' R&D expenditures. Second, direct R&D subsidies facilitate firms' innovation actions. Recent studies that use advanced econometric methods and that control for selection bias reject the hypothesis that public R&D subsidies crowd out private R&D expenditures. Additionally, public subsidies have been found to be effective in encouraging R&D in small and financially constrained firms. Third, R&D tax credits and direct subsidies differ in terms of the periods in which their effects are most significant.

Tax credits are more effective over the short run whereas subsidies have a positive effect over the medium to long run. Fourth, R&D cooperation is important. There are positive externalities between public research and private firms and their R&D expenditures and especially within the same geographically area. Furthermore, research joint ventures between firms and institutions positively affect private innovation by reducing cost barriers to engaging in R&D and by increasing the number knowledge spillovers occurring between participating institutions.

Dechezlepretre and Sato (2017) reviewed the literature on the impacts of environmental regulation on competitiveness. These authors argue, based on empirical evidence, that environmental regulation has both negative effects on productivity in some sectors and for some pollutants but also positive effects on other sectors and for other pollutants. Koźluk and Zipperer (2015) reached a similar conclusion based on their literature review of the empirical findings on effects of environmental policy on productivity growth. These authors suggest that the empirical evidence is inconclusive, as results are usually very context-specific and can support only limited general policy conclusions. However, the impacts of environmental regulation on productivity tend to be short-term and to more or less vanish over the long-term. For instance, Rubashkina et al. (2015) analyzed how environmental regulation affects the competitiveness of the manufacturing sectors of 17 European countries from 1997-2009. These authors investigated the “weak” and “strong” version of the Porter hypothesis (PH). Based on the Porter hypothesis, environmental regulation might encourage innovation (weak form of PH) and further enhance productivity when regulated firms apply new and more productive innovations or make production processes more efficient (strong form of PH). This phenomenon may yield both environmental and economic benefits. Rubashkina et al. (2015) found that environmental regulation leads to an increase in patent applications, supporting the weak version of the Porter hypothesis, but showed that it has no impact on R&D expenditures. On the other hand, more stringent environmental regulation does not harm productivity over a one- or two-year period. The overall productivity effect is neutral, and thus the evidence does not support the strong version of the Porter hypothesis.

Franco and Marin (2017) adopted a similar approach. These authors studied the effects of environmental taxes on innovation and productivity in manufacturing sectors in eight European countries for 2001-2007. However, the authors separated the effects of taxes within a given sector from the role of environmental taxes in upstream and downstream sectors in terms of input–output relationships. The authors found that environmental regulatory stringency is positively related to both innovation and productivity. Downstream regulatory stringency has the strongest effect. Downstream regulatory stringency positively affects both innovation and productivity. Within-sector regulatory stringency does not affect innovation and only stimulates productivity whereas upstream regulatory stringency has no or negative effects. Environmental taxes influence productivity both directly and indirectly through innovation.

Firm-level studies

While country-level studies may suffer from a variety of endogeneity problems, firm-level micro-econometric studies using appropriate econometric methods provide more accurate estimates of the impacts of environmental regulation on companies' willingness to innovate. Many of the estimated effects are, however, very similar to those found in country-level studies.

For example, energy prices and spillovers matter. Aghion et al. (2016) found, in studying firms’ patents in the auto industry, that higher tax-inclusive fuel prices cause firms to redirect technical change towards clean innovation. In addition, path dependency through firms’ own patenting histories and aggregate patenting also has an effect. Firms tend to innovate more in clean technologies when they have a history of patenting in clean technologies. Moreover, local knowledge spillovers cause firms to patent more in clean innovations when they are based in countries in which other firms have also been undertaking more clean innovations (and vice versa for dirty technologies).

Calel ja Dechezleprêtre (2016) offered similar insights in analyzing the EU Emissions Trading System and its impacts on firm innovation. These authors found that carbon pricing by the EU ETS has increased low-carbon innovation among EU ETS firms by 10 percent without crowding out patenting for other technologies. However, the EU ETS has not had spillover or crowding-out effects and has not affected patenting beyond the set of regulated companies. The EU ETS has increased levels of European low-carbon patenting overall by only 1 percent relative to a counterfactual scenario.

Public R&D grants for early-stage technologies can be very effective. Howell (2017) analyzed the US Department of Energy’s (DOE) Small Business Innovation Research (SBIR), according to which R&D subsidies were granted to the best-ranked projects over two phases. First-stage winners could apply later to a larger award given in the second stage. Howell shows that securing an early-stage award approximately doubled the probability of a firm receiving subsequent venture capital, and it thus did not crowd out private investments. This award also had large, positive impacts on patenting and revenues. Later-stage awards did not have any measurable effects except for a small positive effect on patenting. Howell also argues that the effects of early-stage grants come through a prototyping channel and not because award status would serve as a signal of a project's quality. Early stage subsidies are useful because they fund mostly technology prototyping where a grant makes it possible to conduct proof-of-concept work that would not be financed without a grant.

One of the main reasons to support firms' R&D actions is rooted in knowledge spillovers. In other words, firms benefit from R&D executed by other firms, as they may also use the "spilled" knowledge related to new technologies. However, as pointed out by Bloom et al. (2013), R&D may also involve negative externalities. This observation emerges through product market competition. When a company engaged in R&D is a product market rival to other firms, then the R&D executed may have a negative influence on other firms' value through the business stealing effect by reducing other firms' profit margins or market shares. Bloom et al. (2013) studied these two countervailing spillovers from a panel of U.S. firms for 1981 to 2001. These authors found that both technology and product market spillovers are present but that technology spillovers dominate, and thus the social returns of R&D are higher than private returns. The authors also found that technology spillovers are present in all of the studied sectors. However, smaller firms secure lower social returns than larger firms. Hence, it is important to look critically at the extensive subsidization of small firms' R&D unless there are other reasons to support them (e.g., liquidity constraints or enhancing competition).

Related to Bloom et al.'s (2013) findings, Aghion et al. (2015) show that competition and competition-friendly policies enhance productivity and productivity growth. Aghion et al. (2015) used data on medium-sized and large enterprises operating in China between 1998 and 2007. Competition-friendly policies, such as subsidies or tax policies, are more effective in supporting productivity growth when targeted towards more competitive sectors or industries. These authors defined competition-friendly policies as policies that are more dispersed across firms or that encourage younger and more productive enterprises. Noailly and Smeets (2015) made a similar argument based on their study of the energy sector. Their study used patent on in fossil fuel (FF) and renewable energy (REN) technologies for 5471 European firms for the 1978–2006 period. Noailly and Smeets (2015) argued that it is the entry of specialized renewable energy firms following the growth of renewable energy markets that decreases the gap between fossil fuel-based and renewable energy technologies. On the other hand, increases in fossil fuel technology prices, market sizes, and knowledge stocks increase the technology gap. This observation emerges from the innovation rates of firms using both fossil fuels and renewable energy technologies. As a policy implication Noailly and Smeets (2015) argued that to enhance renewable energy innovation, it is important to support small firms to start and sustain innovation over the long run.

5 Data and descriptive findings

5.1 Data

The data on R&D and policy indicators used in the empirical analysis are obtained from the databases of the OECD and International Energy Agency (IEA). The data and variables used in the empirical analysis are described below.

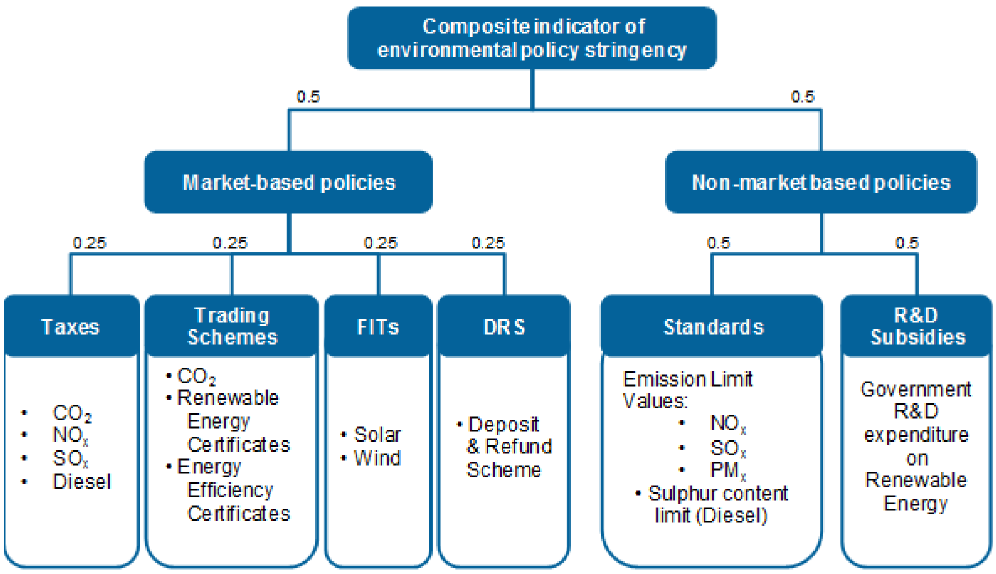
The data on energy technology Research, Development and Demonstration (RD&D) budgets are obtained from the IEA. These data include country RD&D budgets summarized for several industries. In the analysis, we concentrate on the following technology groups: energy efficiency and renewable energy sources. We utilize data on total RD&D budgets in millions of USD, measured in 2010 prices and Purchasing Power Parities (PPPs). Based on these data, we construct a variable for "green" RD&D by summing the above measures for energy efficiency and renewable energy. The exact classifications used for the technology groups are provided in IEA documentation (IEA, 2018).

We obtain information on environmentally related tax revenues from the OECD *Policy Instruments for the Environment* database, developed jointly with the European Environmental Agency (EEA). The variable for environmentally related tax revenue captures environmentally related tax revenues as a percentage of GDP. The total tax revenues are computed over seven environmental domains, including energy products (fossil fuels and electricity) that also cover vehicle fuels and all CO_2-related taxes; motor vehicles and transport; ozone-depleting substances; water and wastewater; waste management; mining and quarrying; and unallocated taxes not included elsewhere.

We extract data on environmental protection subsidies and transfers from the OECD's *Environmental Protection Expenditure and Revenues* dataset. In the empirical analysis, we use environmental protection subsidies and transfers (in millions of USD, measured in 2010 prices and PPPs). However, the country coverage of this measure is incomplete, and its content varies across countries, which limits its applicability to the analysis. In the case of Finland, these data for subsidies and transfers consist of paid subsidies and transfers, including R&D subsidies.

We also utilize the Environmental Policy Stringency (EPS) Index obtained from the OECD. This variable serves as a country-specific measure of the stringency of environmental policies that varies from 0 (not stringent) to 6 (highly stringent). In this measure, stringency is defined as the degree to which environmental policies impose an either implicit or explicit prices on polluting or other environmentally harmful behavior. The EPS index is based on the components of 14 environmental policy instruments that relate mostly to climate and air pollution. The structure of the composite EPS index is illustrated below:

Figure 4. EPS index structure



Source: OECD (Botta & Koźluk, 2014)

In this study, we focus on the following stringency measures: overall stringency; taxes; trading schemes: green and white certificates; and feed-in tariffs: wind and solar. The overall stringency measure – the composite EPS index – is the aggregate of market and nonmarket indicators that are both given equal weight. The tax indicator represents the stringency of CO2, NOx, SOx and diesel taxes. These tax subcomponents are each given equal weight. The green trading scheme indicator covers obligations to obtain a certain percentage of electricity from green sources. Higher percentages indicate more stringent policies. The white trading scheme indicator measures the stringency of schemes in terms of the amount of annual energy savings measured in kWh. A higher level of energy savings indicates more stringent policies. The feed-in tariff wind and solar indicators measure the stringency of feed-in tariffs for wind and solar photovoltaic energy, respectively.

The empirical analyses utilize data based on constant prices and common currencies. We obtain data on U.S. dollar exchange rates, Purchasing Power Parities (PPPs), GDP in National Currencies and in U.S. dollars, and GDP deflators from OECD databases.

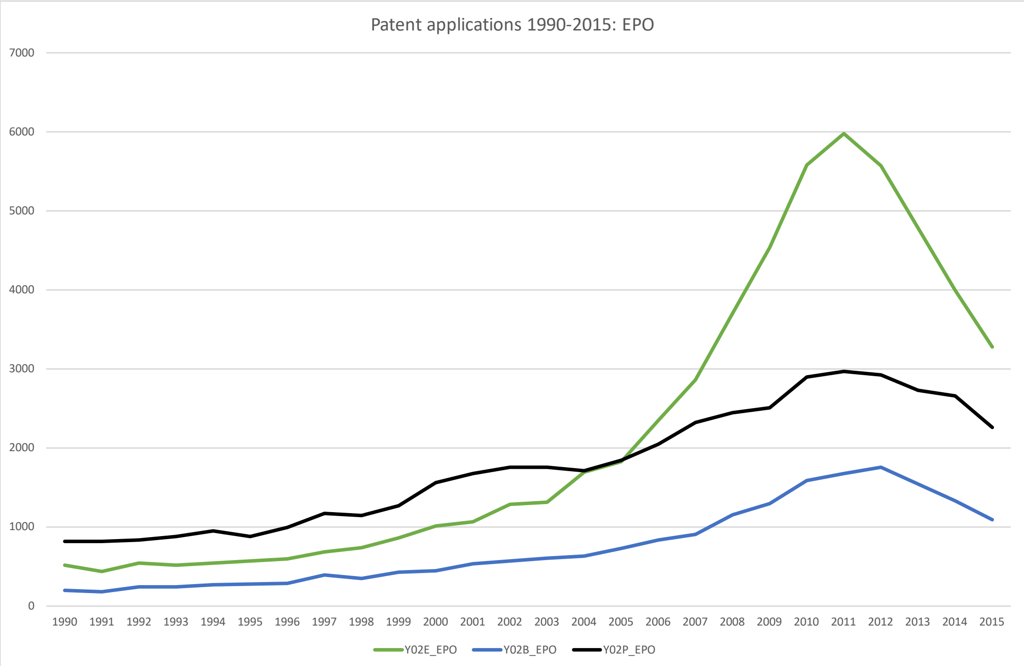
The country-level panel dataset is constructed as follows. We use RD&D country budget data as a starting point given its coverage of country-specific observations. We then merge the rest of the datasets to these data by country code and year. We focus on OECD countries and the post-1990 time period. Some data used in the analysis, i.e., environmentally related tax revenues and environment protection subsidies and transfers, are available for shorter time periods starting from the mid-1990s onward. Furthermore, some of the data and variables used in the analysis are available only for a smaller set of countries. We construct separate datasets for patenting data obtained from the EPO and USPTO.

The independent variables used in the estimations are as follows: *RD renewables & energy efficiency (t-1)* measures “green” RD&D and is defined as a natural logarithm of the sum of lagged energy efficiency and renewable RD&D budgets. *Environmental policy stringency (t-1)* measures used in the estimations include the lagged EPS composite index as well as the EPS sub-indexes for *green* and *white trading-scheme certificates* and *feed-in tariffs for wind* and *solar*. Higher values for the EPS indexes indicate more stringent policies. *RD subsidies* is a natural logarithm of subsidies and transfers (including R&D) measured in millions of USD and in 2010 prices and PPPs. The *Kyoto ratification dummy* takes a value of one after ratification and zero otherwise. The *Electricity market dominant firm* dummy is a proxy for the order of magnitude of competition in electricity markets: the variable takes a value of one when the market share of the largest company in the electricity industry is greater than 90 percent and a value of zero otherwise. *GDP* is a natural logarithm of GDP measured in millions of USD from 2010 prices and PPPs.

5.2 Patented green ideas

Our data cover all patent applications filed with the EPO and USPTO from 1990 to 2015 under the following three CPC code categories: i) Y02E (i.e., reduction of greenhouse gas emissions related to energy generation, transmission or distribution), ii) Y02B (i.e., climate change mitigation technologies related to buildings) and iii) Y02P (i.e., climate change mitigation technologies for the production or processing of goods).[6] The data were extracted from the PatentInspiration database (www.patentinspiration.com).

Figure 5. Patent applications filed with the European Patent Office: 1990-2015



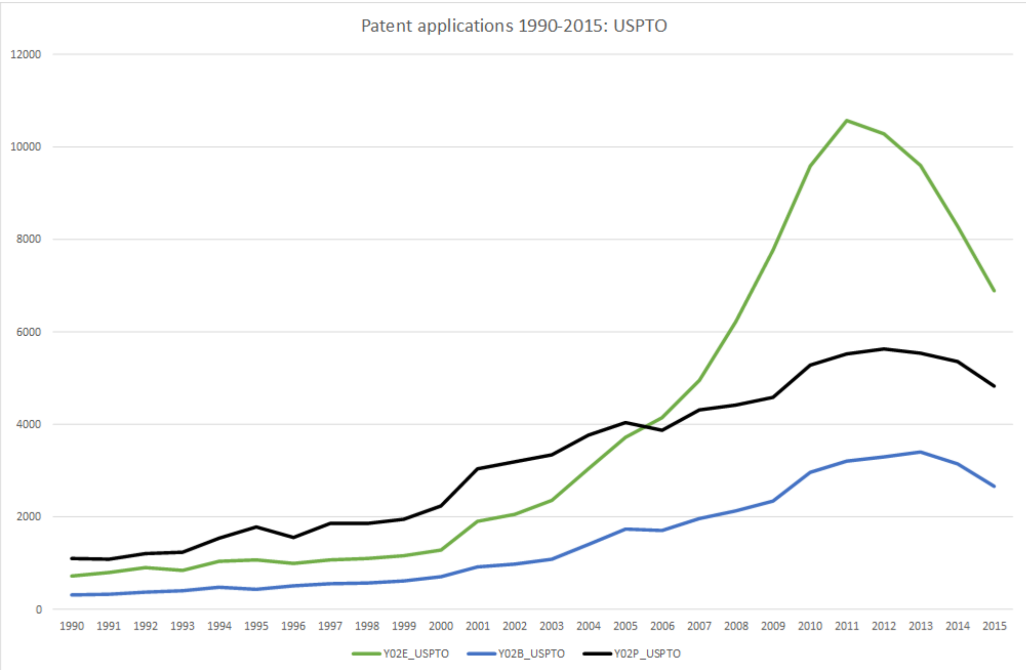
Data source: Patentinspiration.com

Figures 5 and 6 illustrate that the number of patent applications filed in the sampled technology fields follows a similar pattern over time in the United States and in Europe. There was a slight upward trend in the number of filed patent applications for all of the sampled environmentally related technologies from the early 1990s to the mid-2000s. After the Kyoto Protocol came into force in 2005, both the USPTO and EPO witnessed strong growth in the number of filed patent applications concerning technologies designed to reduce greenhouse gas emissions to 2010. The number of annually filed

[6] Annex 1 provides a detailed description of the technology fields that these CPCs cover.

patent applications concerning climate change mitigation technologies related to buildings and to the production or processing of goods increased more moderately in the same time period. After 2011, there is a sharp (slight) decrease in the number of Y02E patent applications concerning greenhouse gas emission reductions (Y02B and Y02P patent applications concerning climate change mitigation technologies).

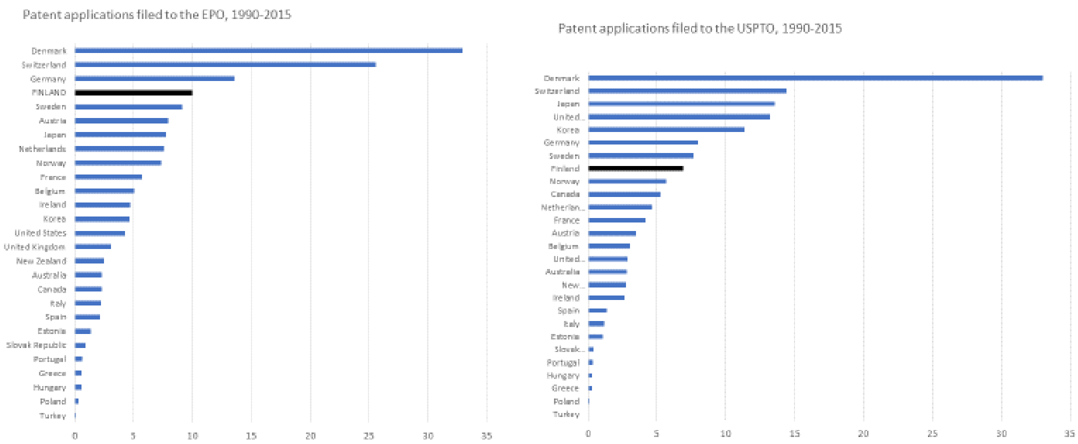
Figure 6. Patent applications filed with the United States Patent and Trademark Office: 1990-2015



Data source: Patentinspiration.com

Figure 7 shows that Denmark is the leading country both in Europe and the United States in terms of the total number of patents filed per capita from 1990 to 2015 for technologies designed to reduce greenhouse gas emissions. Denmark's policy has strongly focused on supporting renewable energy forms, particularly wind energy. Denmark began to promote wind energy from the mid-1970s. The Danish R&D support program established in 1976 for all energy areas including wind energy was followed with investment subsidies for the installation of wind turbines (1979-1989). From the mid-1980s private wind turbine owners received a partial refund for energy and environmental taxes. In 1993, the feed-in tariff for wind energy was introduced. Utility companies were obligated to purchase electricity from wind producers at a rate that 85 percent of consumer prices. In 2001, feed-in tariffs were modified towards a premium-based system, in which a premium is paid in addition to the electricity market price.

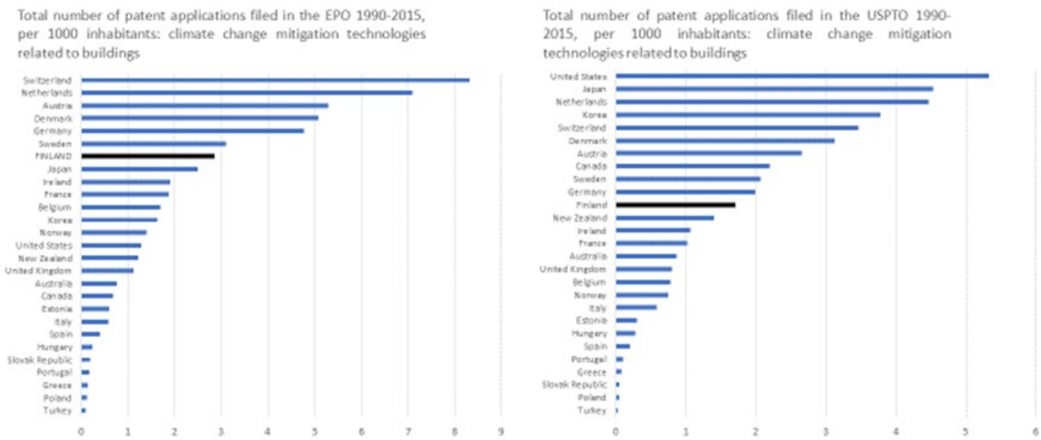
Figure 7. Number of patent applications filed with the EPO and USPTO from 1990-2015 per 1000 inhabitants: reduction of greenhouse gas emissions related to energy generation, transmission or distribution



Data source: Patentinspiration.com

Finland ranked fourth in the number of EPO patentees (per capita) for this renewable technology field. However, Finland is positioned eighth in the list of sample OECD countries when measured by the number of patent applications filed to the USPTO. These data illustrate that the Finnish (unlike, e.g., the Danish) seek patent protection for renewable energy inventions relatively more often in Europe-wide markets than in the United States.

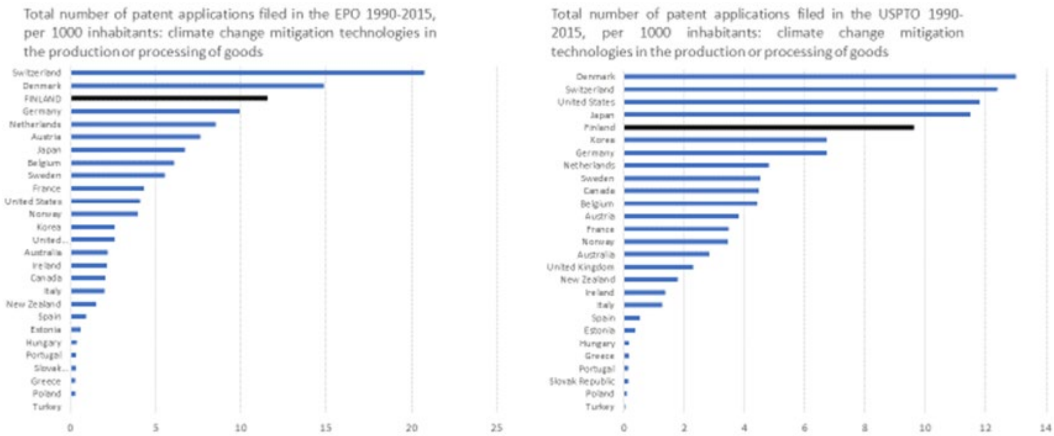
Figure 8. Number of patent applications filed with the EPO and USPTO from 1990-2015 per 1000 inhabitants: climate change mitigation technologies related to buildings



Data source: Patentinspiration.com

Finland also ranks relatively highly in patent applications filed regarding climate change mitigation technologies for the production or processing of goods and related to buildings. Additionally, for these categories, and particularly in green innovation related to production, Denmark is one of the top countries. The United States clearly appears to be the number one country in patent applications filed with the USPTO concerning climate change mitigation technologies related to buildings. This descriptive finding likely reflects a home market bias or a higher propensity for organization's based in the United States to file patent applications in their home country.

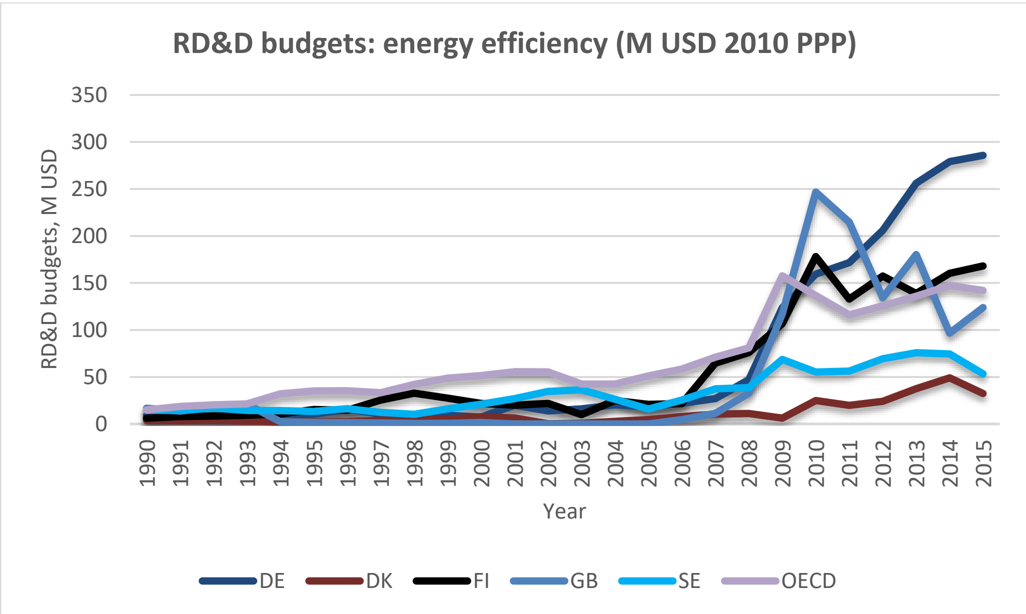
Figure 9. Number of patent applications filed with the EPO and USPTO from 1990-2015 per 1000 inhabitants: climate change mitigation technologies for the production or processing of goods

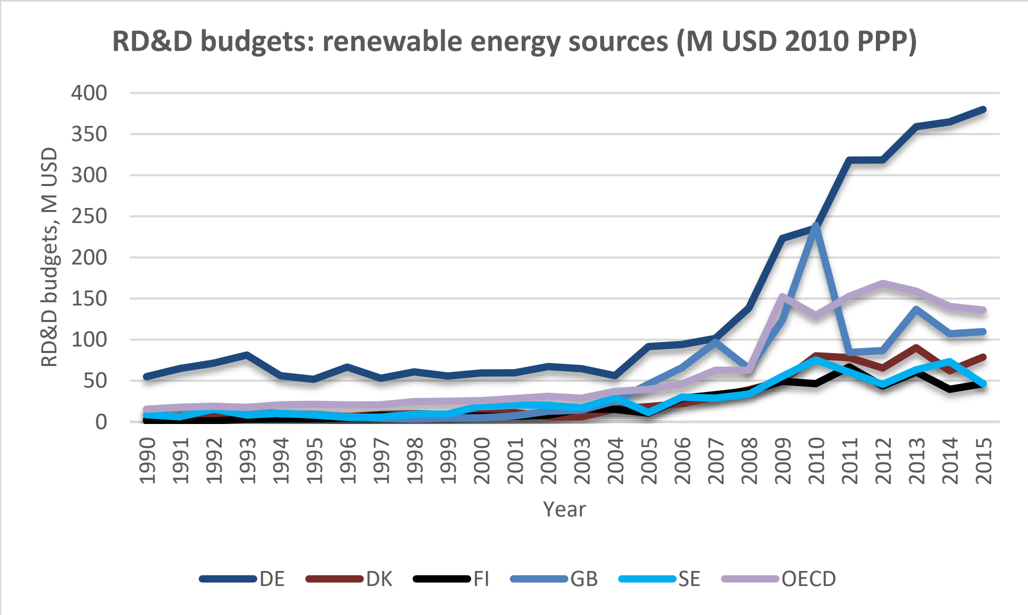


Data source: Patentinspiration.com

5.3 Environmental policy indicators

Figure 10. RD&D Budgets (USD 2010 PPP)

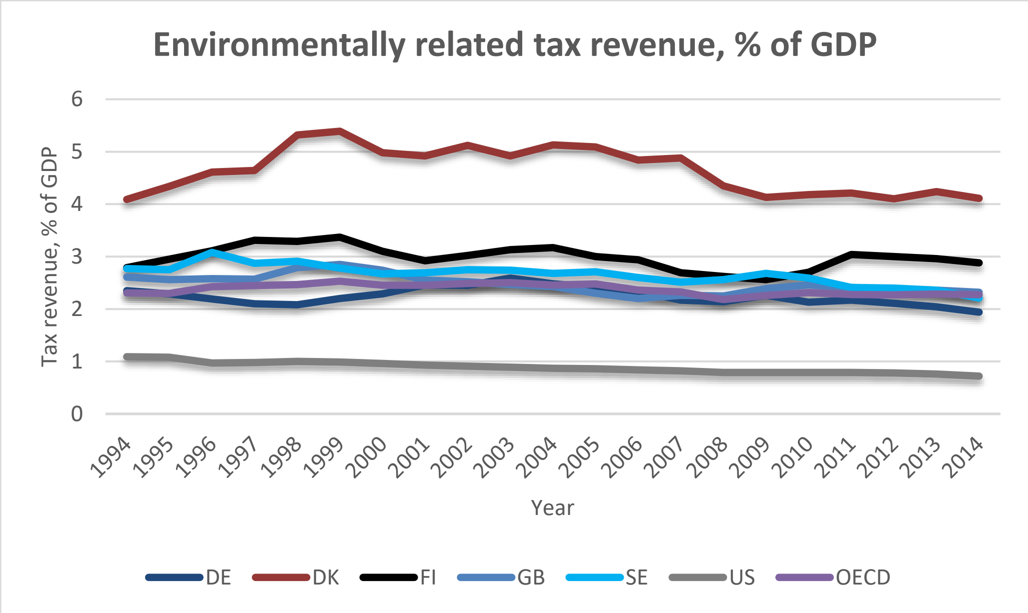




Source: IEA

Figure 10 shows country-level RD&D budgets summarized for the following technology groups: energy efficiency and renewable energy sources. We exclude the United States from the figures because it dominates RD&D budget levels of each group to such a degree that it would render the comparison of other countries problematic. For the rest of the countries, Germany stands out in energy efficiency and renewable energy source technology groups with notably higher RD&D budgets.

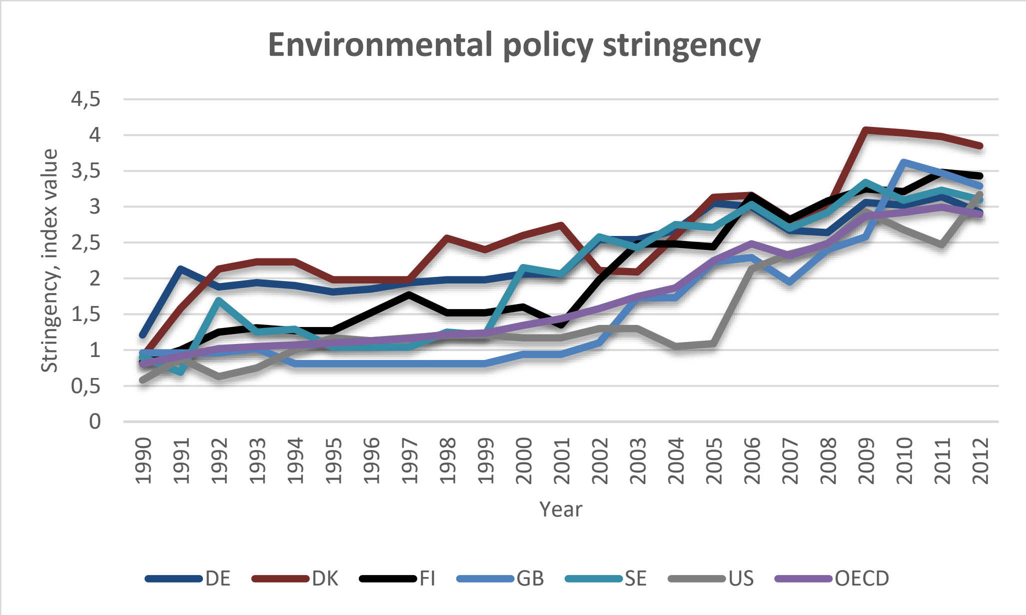
Figure 11. Environmentally related tax revenue, percent of GDP



Source: OECD

Figure 11 shows the environmentally related tax revenue as a percentage of GDP for various OECD countries. Denmark stands out from the rest with the largest tax percentages, whereas the United States is at the opposite end of the spectrum with the lowest tax percentages. Finland ranks above the United Kingdom, Sweden, Germany, and the OECD average.

Figure 12. Environmental policy stringency



Source: OECD

Figure 12 illustrates environmental policy stringency based on the OECD's composite EPS index. The figure shows that environmental policies have become more stringent over time, particularly in the 2000s. Based on the index, Denmark adopted some of the most stringent policies over the time period. In 2012, when most of the country-specific series end, Finland is in second place in terms of stringency, ranking above the United Kingdom, the United States, Sweden, Germany, and the OECD average.

6 Empirical analysis and findings

We first estimated the models for green innovation using as our dependent variable the aggregate number of patent applications filed with the EPO/USPTO in the three green technology classes (i.e., those covering CPC codes Y02E, Y02B and Y02P) by an applicant from a given country (see section 5.1). Second, we investigated whether the relationship between the policy indicators and patenting activities varies by technology category (see section 5.2). The non-negative values of the dependent variable call for the use of an econometric model designed for such variable. We use the fixed effects Poisson model to control for unobservable country-specific heterogeneity that may affect both the applicant's propensity to apply for patents and the magnitude of patent applications of a certain technology area. To obtain unbiased estimates, we employ the fixed effects Poisson model with robust standard errors i) clustered by country in estimations for the aggregate count of filed patent applications and ii) clustered by country and technology class in estimations for separate counts of filed patent applications made in different technology classes. This approach allows for error correlations within clusters over time.

We first estimated a basic model (Model 1) with only public R&D expenditures allocated to renewable energy sources and energy efficiency and the overall environmental policy stringency index. In the estimations for separate technology classes (Section 4.2.2), these variables were multiplied by the dummy variables for each technology category to estimate the technology-specific relationship between the variables of interest and the number of patents filed in each technology category. The impact of policy measures aimed at increasing the use of renewable energy sources in the production of electricity were assessed only for the relevant patents, i.e., applied patents of CPC class Y02E (i.e., the reduction of greenhouse gas emissions related to energy generation, transmission or distribution). Such policy measures include green certificates and feed-in tariffs, and policy stringency measures for these were thus multiplied only by the dummy variable for technology class Y02E. White certificates also obligate energy (typically electricity and gas) suppliers or distributors, but the mechanism is designed to promote end-user energy savings. Thus, white certificates may facilitate the invention not only of efficient technologies generating, transmitting or distributing electrical power but also of those mitigating climate change through building and production processes.

Given that environmental policy is likely to affect innovation and patent application filings with a lag, we lagged all policy variables used in the estimations. We further controlled for country GDP and included annual dummy variables to capture time-related variations in the filed green technology patent applications.

In Model 2, we extended the set of explanatory variables to cover the various measures of environmental policy stringency discussed in section 4.1. Many of the underlying policy measures were not employed in any country until the early 2000s, and for certain measures implementation was limited to only a small number of countries by the end of the sample period. For instance, in 2015, a white certificate trading scheme was in use in only five of the sampled countries.

Unfortunately, the variable “RD subsidies t-1” capturing environmental subsidies and transfers included a substantial number of missing observations. Therefore, we separately estimated Model 3 with all explanatory variables of Model 2 and the variable measuring the magnitude of RD subsidies. All of the models are estimated for 2010-2015.

6.1 Estimation results for the aggregate number of filed green patent applications

The estimation results given in Table 2 and 3 indicate, as expected, that public R&D investments made on renewable energy forms and energy efficiency relate positively to patented green innovation at the aggregate level. The estimated coefficient for the composite index of environmental policy stringency does not appear to be statistically significant for any of the estimated models. Instead, when we control for the stringency of different environmental policy instruments in the estimations (Model 2), we find that the variable capturing the stringency of tax policy relates positively and highly statistically significantly to the count of green patent applications filed with the EPO. Policy stringency concerning green and white certificates are, respectively, negatively and positively related to patented green innovation in Europe (but not in the United States). The estimated coefficient of the variable “elect market dominant firm” used as a proxy for the degree of competition in electricity markets is not statistically significant.

Table 2. Estimation results of the Poisson Fixed Effects models for the aggregate count of green patent applications filed with the EPO

Dep. variable: Aggregate patent count for all tech	Model 1	Model 2
RD renewables&energy eff. t-1	0.053*	0.015
	(1.85)	(0.63)
Environmental policy stringency t-1	-0.030	-0.030
	(-1.30)	(-1.47)
Policy string taxes t-1		0.109***
		(2.83)
Policy string green certif t-1		-0.060***
		(-4.00)
Policy string white certif t-1		0.047***
		(2.81)
Policy string feedintariffs wind t-1		-0.015
		(-1.43)
Policy string feedintariffs solar t-1		0.005
		(0.41)
elect market dominant firm		-0.044
		(-0.78)
kyotorat_dmy		-0.175**
		(-2.39)
GDP	0.702	1.553***
	(1.05)	(3.03)
Observations	315	289
Year dummies	Yes	Yes

z statistics are shown in parentheses
* *p* < 0.10, ** *p* < 0.05, *** *p* < 0.01

Table 3. Estimation results of the Poisson Fixed Effects models for the aggregate count of green patent applications filed with the USPTO

Dep. variable: Aggregate patent count for all tech	Model 1	Model 2

RD renewables&energy eff. t-1	0.127***	0.083*
	(4.12)	(1.79)
Environmental policy stringency t-1	-0.038	0.029
	(-1.18)	(0.67)
Policy string taxes t-1		0.014
		(0.32)
Policy string green certif t-1		-0.020
		(-0.89)
Policy string white certif t-1		0.035
		(1.10)
Policy string feedintariffs wind t-1		-0.015**
		(-2.47)
Policy string feedintariffs solar t-1		0.000
		(0.02)
elect market dominant firm		0.004
		(0.02)
kyotorat_dmy		-0.285**
		(-2.27)
GDP	0.881	1.026
	(1.23)	(1.28)
Observations	304	264
Year dummies	Yes	Yes

z statistics are shown in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The data concerning environmental subsidies and transfers are incomplete, leaving only 11 of the sampled countries to the estimated equations. The estimations indicate that the relationship between R&D subsidies and filed green EPO patent applications is not statistically significant, while the relationship is negative and statistically significant for patent applications filed with the USPTO.

Table 4. Estimated coefficients of the Poisson fixed effect model for R&D subsidies

Dep. variable: Aggregate patent count for all tech	EPO	USPTO
	Model 3	Model 3
RD subsidies t-1	-0.032	-0.180^{***}
	(-0.84)	(-2.82)
Observations	119	117
Year dummies	Yes	Yes

z statistics are shown in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Comprises further other explanatory variables of Model 2.

The EPO data suggest that there is a statistically significant relationship between the filed green patent applications and the policy stringency measure for green and white certificate schemes. The adoption of green and white certificate schemes has taken place gradually over time among the sampled countries, and only a few countries had implemented the white certificate scheme by the end of the last sample year. This setting enabled us not only to estimate models that capture correlations between the policy stringency measures and green patenting activities but also to explore their causal relationship. We use the difference-in-differences model to investigate the difference in the number of filed green patent applications in the "treated" countries, i.e., those that have adopted the green and/or white certificate schemes, before and after the implementation of the certificate scheme policies. The difference-in-differences model eliminates the potential bias that may arise from permanent or time-invariant differences between countries that adopted a certain policy and other countries even without the implementation of policies.

Table 5 presents the estimation results of the difference-in-differences models. The first column shows the results for the Poisson fixed effects model, and the second column presents the results for the "traditional" linear fixed effects model with normally distributed errors. The estimated coefficient of the variable “after implementation X treated” captures the difference in the number of applied patents between countries that adopted the green/white certificate scheme and those that did not adopt the schemes after the policy was implemented in the treated countries. Our estimations suggest that those countries that have adopted the green certificate scheme have applied for statistically significantly fewer green patents from the EPO and USPTO after the policy’s implementation compared with the other countries. Instead, the estimation results provide evidence showing that since the implementation of the white certificate scheme, these countries have filed more green patent applications than those not adopting the white certificate scheme.

Table 5. Estimation results of the difference-in-differences models for the aggregate count of green patent applications

Dep. variable: Aggregate patent count for all tech	Poisson diff-in-diff count	FE model diff-in-diff log count
EPO		
Green cert: after implementation X treated	-0.153** (-2.08)	-0.345*** (-3.48)
White cert: after implementation X treated	0.167** (2.43)	0.195** (2.40)
Observations: 277		R-square: 0.64
USPTO		
Green cert: after implementation X treated	-0.277*** (-3.56)	-0.344* (-1.97)
White cert: after implementation X treated	0.309** (2.11)	0.133 (0.66)
Observations: 252		R-square: 0.67

z statistics are shown in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

6.2 Technology-specific estimation results

The estimation results given in Table 6 and 7 suggest that public R&D expenditures covering renewable energy sources and energy efficiency relate positively to the number of filed patent applications concerning technologies aimed at reducing greenhouse gas emissions related to energy generation, transmission and distribution. The relationship is particularly strong for patent applications filed with the USPTO. It seems, however, that relatively higher "green" R&D expenditures do not relate clearly statistically significantly or relate negatively with patent applications for climate change mitigation technologies related to buildings and production. As a plausible explanation for these empirical findings, government R&D in the sampled OECD countries is rather focused on technologies promoting green energy generation, while innovation in climate change mitigation technologies for production is more heavily driven by private companies.

Table 6. Technology-specific estimation results of the Poisson Effects models for patent applications filed with the EPO

Dep. var: Patent count	Model 1	Model 2
RD renewables&energy eff. t-1 x Y02E	0.134*	0.143*
	(1.81)	(1.93)
RD renewables&energy eff. t-1 x Y02B	-0.005	0.036
	(-0.07)	(0.51)
RD renewables&energy eff. t-1 x Y02P	-0.038	-0.180***
	(-0.78)	(-2.74)
Policy string taxes t-1 x Y02E		0.070
		(0.77)
Policy string taxes t-1 x Y02B		0.135***
		(2.73)
Policy string taxes t-1 x Y02P		0.210***
		(3.03)
Policy string green certif t-1 x Y02E		0.015
		(0.35)

Policy string white certif t-1 x Y02E		0.020
		(0.92)
Policy string white certif t-1 x Y02B		0.033^{*}
		(1.75)
Policy string white certif t-1 x Y02P		0.045^{**}
		(2.13)
Policy string feedintariffs wind t-1 x Y02E		-0.040^{***}
		(-4.32)
Policy string feedintariffs solar t-1 x Y02E		0.038^{**}
		(2.39)
elect market dominant firm x Y02E		0.160
		(1.54)
kyotorat_dmy x Y02E		0.069
		(0.38)
kyotorat_dmy x Y02B		-0.086
		(-0.46)
kyotorat_dmy x Y02P		-0.247
		(-1.24)
GDP	0.792	1.216
	(1.19)	(1.51)
Observations	945	867
Year dummies	Yes	Yes

z statistics are shown in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7. Technology-specific estimation results of the Poisson Effects models for patent applications filed with the USPTO

Dep. var: Patent count	Model 1	Model 2
RD renewables&energy eff. t-1 x Y02E	0.222*** (2.67)	0.246*** (2.86)
RD renewables&energy eff. t-1 x Y02B	0.114* (1.67)	0.129 (1.62)
RD renewables&energy eff. t-1 x Y02P	0.014 (0.20)	-0.112 (-1.55)
Policy string taxes t-1 x Y02E		0.011 (0.20)
Policy string taxes t-1 x Y02B		-0.038 (-0.43)
Policy string taxes t-1 x Y02P		0.095 (1.50)
Policy string green certif t-1 x Y02E		0.100** (2.40)
Policy string white certif t-1 x Y02E		0.008 (0.34)
Policy string white certif t-1 x Y02B		0.000 (0.00)
Policy string white certif t-1 x Y02P		0.052* (1.65)
Policy string feedintariffs wind t-1 x Y02E		-0.027** (-2.05)
Policy string feedintariffs solar t-1 x Y02E		0.045*** (3.20)
elect market dominant firm x Y02E		0.404* (1.72)
kyotorat_dmy x Y02E		0.540*** (3.58)
kyotorat_dmy x Y02B		0.471*** (3.17)
kyotorat_dmy x Y02P		0.280**

		(2.25)
GDP	0.964	1.238
	(1.28)	(1.28)
Observations	914	794
Year dummies	Yes	Yes

z statistics are shown in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The estimation results indicate that there are technology-specific differences in the relationship between the applied environmental policy instruments and patenting activities. A more stringent taxation of pollution relates positively to the number of patent applications concerning climate change mitigation technologies related to buildings and production filed with the EPO. Our data thus suggest that higher tax rates for emissions may create strong incentives to develop such innovations related to buildings and production processes that mitigate the detrimental effects of climate change. The stringency of policies related to green certificates, or the higher percentage at which energy providers are obligated to source supplied electricity from green sources, does not relate to patent applications filed for green innovation with the EPO. However, the estimated coefficient of the variable “Policy string green certify t-1 x Y02E” is positive and statistically significant for patent applications filed with the USPTO. A more stringent policy concerning white certificates, or the higher the amount of annual energy savings that end-users are obligated to reach, relates positively to green patent applications filed in technology categories related to buildings and production. The relationship is not strong between the white certificate policy stringency and patented ideas for climate change mitigation technologies related to buildings.

Table 8 reports the estimation results that show no positive relationship between R&D subsidies and filed patent applications for green technology categories for the estimation sample. The estimated coefficient of the variable capturing environmental subsidies and transfers gets a negative and statistically significant coefficient for Y02E patents filed with the USPTO.

Table 8. Estimated coefficients of the Poisson fixed effect model for R&D subsidies

Dep. var: patent count	EPO Model 3	USPTO Model 3
RD subsidies t-1 *Y02E	-0.029 (-0.61)	-0.277** (-2.95)
RD subsidies t-1 *Y02P	-0.015 (-0.23)	-0.057 (-0.69)
RD subsidies t-1 *Y02B	0.078 (0.93)	-0.118 (-0.21)
Observations	381	375
Year dummies	Yes	Yes

z statistics are shown in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Comprises further other explanatory variables of Model 2.

The estimated fixed-effect Poisson models using the difference-in-difference methodology suggest that those countries that have implemented the white certificate scheme have clearly filed more patent applications concerning climate mitigation technologies related to production (with the EPO) and to buildings. The estimated fixed effects models do not take into account the measurement of the data (i.e., the positively skewed distribution of the dependent variable). These models do not effectively explain the variation in the dependent variable, suggesting that the data do not fit well with the linear regression model.

Table 9. Technology-specific estimation results of the difference-in-differences models for the count of green patent applications

Dep. variable: Patent count for technology group i	Poisson dif-in-dif count	FE model dif-in-dif log count
EPO		
Green cert: after implementation x treated x Y02E	0.194 (1.08)	-0.278^{*} (-1.80)
White cert: after implementation X treated x Y02E	-0.044 (-0.36)	-0.034 (-0.23)
White cert: after implementation X treated x Y02B	0.191^{***} (2.59)	-0.229 (-1.53)
White cert: after implementation X treated x Y02P	0.197^{**} (2.53)	-0.009 (0.08)
Observations: 831		R-square: 0.20
USPTO		
Green cert: after implementation x treated x Y02E	0.096 (0.93)	-0.286 (-1.23)
White cert: after implementation X treated x Y02E	0.274 (1.33)	0.106 (0.40)
White cert: after implementation X treated x Y02B	0.186 (1.32)	-0.297 (-1.43)
White cert: after implementation X treated x Y02P	0.385^{**} (2.41)	0.057 (0.30)
Observations: 758		R-square: 0.23

z statistics are shown in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

7 Conclusions

This report sheds lights on environmental policy instruments, green innovation generation and the development of markets for renewable energy forms in OECD countries since the 1990s. We focus on economic or market-based environmental policy instruments, such as subsidies, tradable permits and taxes on pollution, used to facilitate the transition towards clean technology. Our empirical analysis further controls for certain non-market instruments such as government R&D expenditures on energy efficiency and renewable energy forms. Regarding green innovation, we focus on patent applications filed with the EPO and USPTO under the following three technology categories: i) reduction of greenhouse gas emissions related to energy generation, transmission or distribution; ii) climate change mitigation technologies related to buildings and iii) climate change mitigation technologies for the production or processing of goods.

Our descriptive analysis indicates that both the number of filed green patents and the share of energy generated from renewable energy forms increased moderately from 1990 to 2005. After 2005, there was clearly stronger growth in green innovation and an expansion in markets for energy generated from renewable sources. The development paths of the countries differ, however, due to the different production structures and policies adopted. The northern European countries – Denmark, Sweden and Finland – are among the top ten countries in the world in terms of the total number of patents filed per capita from 1990 to 2015 in the covered green technology areas.

Our empirical analysis offers some new insights on the relationship between environmental policy instruments and green innovation. The data suggest that the adoption of white certificate schemes promoting end-user energy savings has facilitated green innovation. Various reports describe the implementation of white certificate schemes and suggest, based on the descriptive statistics, that they have resulted in substantial energy savings. These findings suggest that it might be worthwhile to explore in more detail the costs and benefits of white certificate schemes in the Finnish context.[7] Our estimation results provide further support for the positive relationship between the stringency of taxation on fossil fuels and green innovation. This empirical finding is consistent with some previous studies suggesting that environmental taxes cause firms to redirect technical change towards clean innovation (see, e.g., Aghion et al., 2006; Franco and Marin, 2017). It seems credible that the expected rebates of energy taxes may reduce firms' incentives to invest in R&D targeted at the generation of technologies that reduce greenhouse gas emissions and that thus have adverse impacts on green innovation.

We find that public R&D expenditures covering renewable energy sources and energy efficiency relate positively to the number of patent applications filed concerning technologies aimed at reducing greenhouse gas emissions related to energy generation, transmission and distribution. We cannot draw any strong conclusions on the relationship between environmental R&D subsidies and green innovation due to incomplete data. However, various prior empirical studies suggest that R&D subsidies tend to facilitate innovation. Furthermore, the literature suggests that carbon pricing and R&D subsidies are complementary policies. R&D subsidies play a substantial role in the beginning of the transition towards clean technology. Furthermore, for mature technologies, a certificate system may serve as a cost-efficient way to fulfill renewable energy obligations.

Overall, although R&D subsidies may efficiently complement other policy instruments, it seems that the most powerful tools for promoting green innovation are "reverse subsidies" or taxation-based environmental policy instruments. A stick rather than a carrot (e.g., the obligation for energy suppliers or distributors to achieve a certain energy savings goal or higher fossil fuel taxes) may work better in promoting innovation targeted at the reduction of greenhouse emissions. Furthermore, according to prior studies, renewable energy policies tend to be more effective in countries with liberalized energy markets. Competition and policy actions that lower entry barriers enhance green innovation. However, our proxy variable for competition, which captures whether a

[7] The report of Pöyry Management Consulting (2011) provides an assessment of the applicability of white certificate systems to Finland. They do not, however, make any definite conclusions; a more detailed analysis would be required for the evaluation of the costs and benefits of white certificate scheme in the Finnish context.

country has monopolistic (or monopoly in the) electricity markets, does not clearly relate to green innovation.

We emphasize that the empirical findings presented in this report are preliminary due to the time limits of the project. We aim to continue our empirical work with robustness tests and further explorations of the role of competition (e.g., using alternative measures of competition) and certificate schemes in green innovation.

Annex 1

Technology	CPC code
Reduction of greenhouse gas [ghg] emissions, related to energy generation, transmission or distribution	**Y02E**
Solar energy	
- Solar thermal energy	Y02E 10/40
- Photovoltaic [PV] energy	Y02E 10/50
- Thermal-PV hybrids	Y02E 10/60
Wind energy	Y02E 10/70
Combustion technologies with mitigation potential	Y02E 20/00
Technologies for an efficient electrical power generation, transmission or distribution	Y02E 40/00
Energy generation from fuels of non-fossil origin	Y02E 50/00
Enabling technologies or technologies with a potential or indirect contribution to GHG emissions mitigation	Y02E 60/00
Climate change mitigation technologies related to buildings	**Y02B**
Integration of renewable energy sources in buildings	Y02B 10/00
Energy efficiency in buildings	
- Lighting	Y02B 20/00
- Heating, ventilation or air conditioning [HVAC]	Y02B 30/00
- Home appliances	Y02B 40/00
- Elevators, escalators and moving walkways	Y02B 50/00
- End-user side electric power management and consumption	Y02B 70/00
Architectural or constructional elements improving the thermal performance of buildings	Y02B 80/00
Enabling technologies in buildings	Y02B 90/00
Climate change mitigation technologies in the production or processing of goods	**Y02P**
Technologies related to metal processing	Y02P 10/00
Technologies relating to chemical industry	Y02P 20/00
Technologies relating to oil refining and petrochemical industry	Y02P 30/00
Technologies relating to the processing of minerals	Y02P 40/00
Technologies relating to agriculture, livestock or agroalimentary industries	Y02P 60/00
Climate change mitigation technologies in the production process for final industrial or consumer products	Y02P 70/00
Climate change mitigation technologies for sector-wide applications	Y02P 80/00
Enabling technologies with a potential contribution to greenhouse gas [GHG] emissions mitigation	Y02P 90/00

Source: European patent office (EPO).[8]

[8] https://www.epo.org/searching-for-patents/helpful-resources/first-time-here/classification/cpc.html

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